ANAEROBIC DIGESTION OF WATER HYACINTH AND SLUDGE

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ABSTRACT

The Institute of Gas Technology has been operating an experimental test unit at the Walt Disney World wastewater treatment plant to demonstrate the conversion of water hyacinth and sludge to CH_4 in a solids concentrating digester. Results from two years of operation have confirmed earlier laboratory observations that this digester achieves higher CH_4 yields and solids conversion than those observed in continuous stirred tank reactors. Methane yields as high as 0.49 m^3 kg^{-1} volatile solids added have been obtained during steady-state operation on a blend of water hyacinth and sludge.

Keywords: Biogasification, wastewater treatment, digester design, aquatic plants, biological conversion.

INTRODUCTION

The Gas Research Institute (GRI) has been sponsoring a biomass waste blend gasification project at the Institute of Gas Technology (IGT) since June 1979 to establish the technical and economic feasibility of integrating a biogasification process with a wastewater treatment system using water hyacinth at the Community Waste Research Facility (CWRF) located at the Walt Disney World (WDW) Resort Complex. The use of water hyacinth for secondary and tertiary treatment of domestic sewage sludge has been investigated (Del Fosse, 1977; Cornwall et al., 1977). To

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further evaluate water hyacinth wastewater treatment, five 0.1 ha ponds and a number of smaller vaults were constructed at the CWRF (Hayes et al., 1987). Data obtained, thus far, at the CWRF indicate that the ponds, which treat both primary and secondary effluents at retention times from 3 to 24 d, reduce biological oxygen demand (BOD) and suspended solids by 70% to 90%. A hyacinth-based wastewater treatment process, therefore, can meet secondary treatment standards while providing an additional source of biomass for CH_4 generation.

The prolific growth of hyacinth and the relatively high biodegradability make it a very suitable feedstock for biological conversion to CH_4. Laboratory-scale research by IGT since 1979 has provided information on feed properties, biodegradability, nutritional requirements, kinetics and has led to the development of a new digester for the conversion of water hyacinth/sludge mixtures (Chynoweth et al., 1982,1983; Ghosh et al., 1980). This digester, which is essentially non-mixed, is designed to concentrate solids and thus provides higher solids retention at any given hydraulic residence time. Loading studies in this digester in the range of 1.6 to 6.5 kg volatile solids (VS) m^{-3} d^{-1} indicated that CH_4 yields were 15% to 20% higher and performance was more stable than in the continuously stirred tank reactor (CSTR).

Bench-scale units do not offer the opportunity to duplicate the various field operating conditions encountered in a full-scale hyacinth/sludge gasification system. Also, a laboratory system does not permit evaluation of the major unit operations and processes under actual conditions of feed availability, variability of feed characteristics, and other operating conditions that are difficult to simulate with small-scale equipment. Perhaps more importantly, a laboratory system does not allow concerted operation of all major processes and subsystems, which is vital to the development of an integrated and reliable biogasification system.

These limitations lead to locating a larger-scale biogasification experimental test unit (ETU) at the water hyacinth treatment and growth channels being evaluated at the CWRF. In this ETU, water hyacinth plants harvested from the treatment channels are mixed with sludge removed in the primary wastewater clarifiers and fed to a digester for the production of CH_4 and waste reduction. Design and installation of the ETU was completed in 1983 and a two year biogasification program on water hyacinth/ sludge mixtures was subsequently completed. To verify the laboratory observations and to provide data for scale-up and economic assessment of an integrated water hyacinth based wastewater treatment and biogasification concept were the program objectives.

PROCESS DESCRIPTION

The ETU (Figure 1) was installed on a pad between the experimental wastewater treatment channels at the CWRF. A description of the various processing areas is provided in Figure 2.

Water Hyacinth Preparation

Water hyacinths are harvested from the wastewater treatment channels and are transported to a chopper, which cuts the plants into approximately 5 cm pieces. The chopped plants are subsequently fed to a grinder that reduces the plants to a particle size as low as 0.2 cm. The ground plants are stored in a tank equipped with a mixer. The storage tank is also insulated and cooled to prevent appreciable degradation of the plant material prior to digestion.

Over 182 Mg (wet) of hyacinth were processed through this section during the two year operating period. Initial grinding and pumping tests indicated that water hyacinth up to 0.6 cm in size could be pumped in 5 cm transfer lines without dilution by water. Seasonal variation of water hyacinth quality and composition were minor and had no noticeable effect on digester operations. Even frost damaged plants were easily processed and did not affect performance. Seasonal variation of water hyacinth total solids and volatile solids concentration are presented in Table 1; a typical chemical analysis is in Table 2. A preliminary energy evaluation indicates that less than 2% of the plant energy production (CH_4 equivalent) is required for the water hyacinth

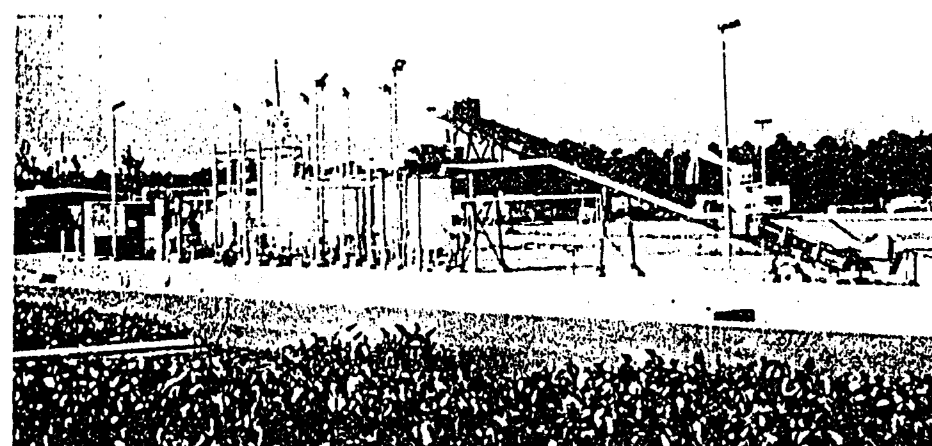

FIGURE 1. Experimental test unit.

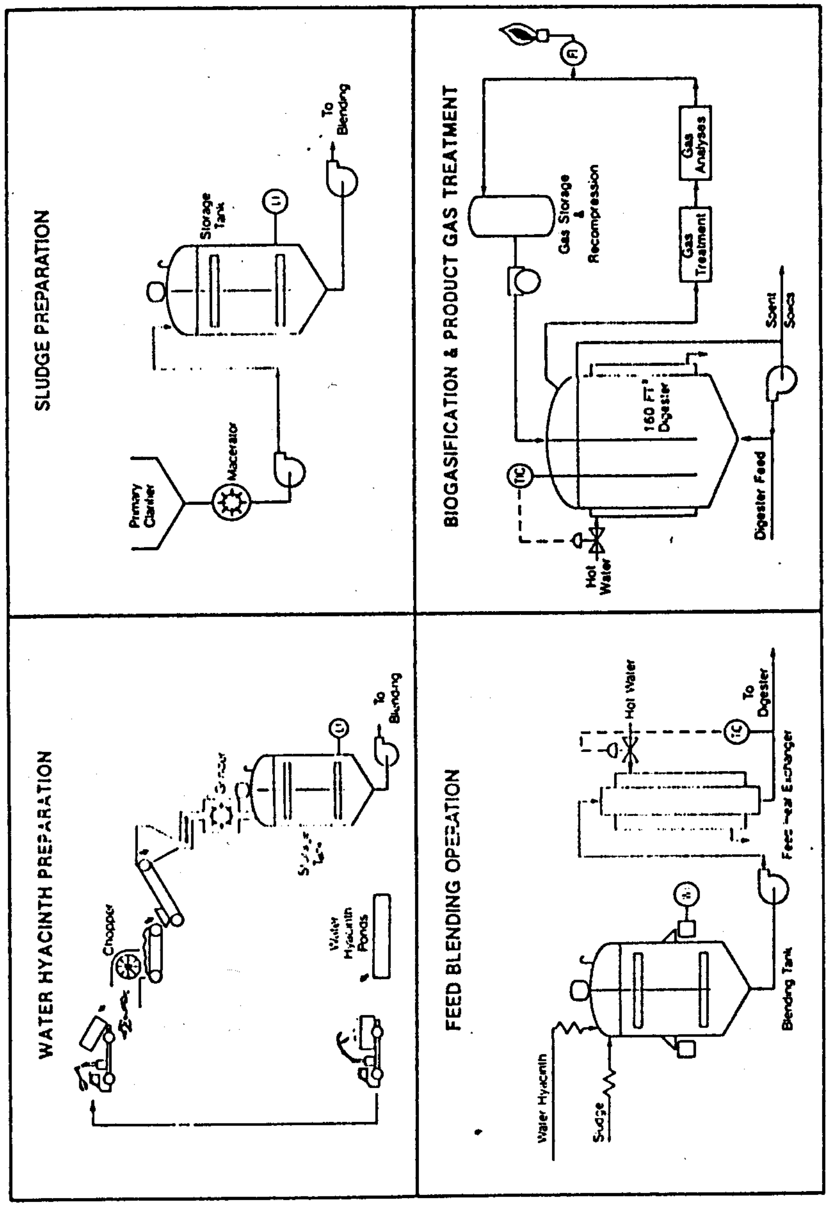

FIGURE 2. Description of the ETU facility.

chopping and grinding operation and as a unit operation is readily scaleable to larger operations.

Sludge Preparation

Sludge is obtained from the primary clarifiers at the wastewater treatment plant. This requires coordination with a full-scale operating plant. The timing and methods of withdrawal from the clarifiers has to be carefully controlled to ensure the transfer of representative and consistent sludge quantities. The

TABLE 1. Seasonal variation of water hyacinth total solids and volatile solids concentration.

Month	Water Hyacinth: Total solids, wt % 1984	1985	Volatile solids, wt % TS 1984	1985
January	--	4.8	--	84.5
February	--	5.0	--	85.8
March	5.4	4.8	85.5	82.1
April	5.4	4.8	83.6	84.4
May	4.7	5.2	82.2	84.4
June	5.4	5.3	85.5	84.6
July	--	5.4	--	86.8
August	--	5.1	--	85.5
September	5.4	4.9	86.5	86.1
October	5.7	5.2	85.5	86.4
November	5.6	4.8	85.3	79.8
December	4.8	4.4	84.5	80.3
Average	5.3	5.0	84.8	84.2
Standard Deviation	0.4	0.3	1.4	2.3

TABLE 2. Typical chemical analysis and heating value for the water hyacinth feed material.

Ultimate Analysis, wt % (dry basis)	
Carbon (total)	43.80
Hydrogen	5.39
Nitrogen	3.73
Sulfur	0.81
Oxygen (by difference)	33.05
Ash	13.22
Total	100.00
Gross Calorific Value, KJ kg^{-1} VS	17,778
Phosphorus Content, wt % (dry basis)	0.73
Ammonia Nitrogen Content, mg L^{-1} (after grinding)	440

sludge is first passed through a macerator to reduce any plastic and other foreign objects to less than 0.3 cm size before being pumped 225 m in a 7.5 cm underground line to a storage tank. A return line allows sludge to first be recycled through these lines to ensure fresh sludge addition to the ETU facility.

This section uses conventional treatment plant equipment and designs, and therefore is also readily scaleable to larger operations. Energy and manpower requirements are not significant.

During the two year operating period the primary sludge solids concentration was lower and fluctuated more than expected. However, this is probably due to the theme park location and is not typical of other municipal locations where concentrations are much more stable at 5 to 6 weight percent. Seasonal data for the sludge solids and volatile solids are given in Table 3. A typical chemical analysis is provided in Table 4.

Feed Blending Operation

Water hyacinth and sludge are blended at the ratios expected from an integrated commercial operation. Based on the water hyacinth growth rates of 56 to 112 Mg (dry wt) ha^{-1} yr^{-1} and channel detention times of three to six days, the water hyacinth to sludge solids weight ratio varies between 2:1 and 1:1 during the year.

In the ETU, the water hyacinth and sludge are blended in a water-cooled tank supported on load cells for weight measurement of the daily feed quantities added to the digester. Automatic timers control feed to the digester at regular intervals and a heat exchanger is provided for preheat of the feedstream. One of

TABLE 3. Seasonal variation of sludge total solids and volatile solids concentration.

	Total Solids, wt %		Volatile Solids, wt % TS	
Month	1984	1985	1984	1985
January	--	3.8	--	91.1
February	--	3.3	--	90.5
March	--	4.1	--	91.2
April	4.0	3.8	91.0	90.4
May	3.8	2.8	91.2	91.0
June	4.4	3.0	91.0	90.5
July	4.0	3.4	89.8	91.7
August	4.2	3.7	82.2	90.2
September	3.7	3.2	87.4	90.0
October	4.2	3.9	88.9	90.4
November	3.8	4.8	90.8	91.5
December	3.8	3.0	91.1	91.1
Average	4.0	3.6	89.3	90.8
Standard Deviation	0.2	0.6	2.9	0.5

TABLE 4. Typical chemical analysis and heating value for the WDW sludge feed material.

Ultimate Analysis, wt % (dry basis)	
Carbon (total)	53.05
Hydrogen	7.41
Nitrogen	3.12
Sulfur	0.38
Oxygen (by difference)	26.42
Ash	0.62
Total	100.00
Gross Calorific Value, kJ kg^{-1} VS	22,650
Phosphorus Content, wt % (dry basis)	0.45
Ammonia Nitrogen Content, mg L^{-1} (as received)	220

the most important considerations at this stage of the development is the accurate determination of solids feed quantities to allow material balance closures and validation of experimental data. This system provided excellent measurement accuracies of 1% to 2% and recalibrations showed that the system maintained its measurement accuracies. Very tight C balances were subsequently calculated around the digester. All balances were better than 100 ± 10%.

Biogasification and Product Gas Treatment

Biogasification of the water hyacinth/sludge mixture occurs in a 4.5 m^3 digester having a height to diameter ratio of 2:1. The maximum feed rate to the digester is 1 Mg d^{-1} of mixed feed containing 5% solids. During the two year operating period the digester was operated as a non-mixed, vertical flow reactor. Start up and operation of the digester provided significant insight into the distribution of solids, pH, volatile acids, and other parameters within the digester during operation with sludge and water hyacinth/sludge blends in the non-mixed mode. These observations were previously not possible in the smaller laboratory reactors. Measurement and analysis of these critical parameters have allowed refinements in operating procedures and have resulted in further performance improvements for this reaction system when compared to conventional stirred tank reactors.

One of the most important observations was that solids distributed differently for sludge and water hyacinth/sludge blends. The blend ratio also affected solids distribution. This led to changes in the operating procedure, and dictated the feed and withdrawal points in the digester for maximum solids retention. Initial operation introduced the feed material into the bottom of the reactor and allowed material to overflow from one of the upper digester nozzles to the waste tank. This procedure was developed under the assumption that solids would settle to the bottom. However, samples taken every foot of reactor height revealed that the water hyacinth/sludge blend had a tendency to accumulate higher solids concentrations at the top of the digester. This was confirmed for both 2:1 and 1:1 water hyacinth/sludge blend ratios.

These observations along with volatile acid and pH profile data led to the development of the solids concentrating (SOLCON) digester. This digester is fed from the top and withdraws and partially recirculates some of the culture from the bottom nozzles of the digester. This concept maximizes solids retention times and conversion for the water hyacinth/sludge blends. No nutrient addition or pH control is required for stable digester operation. Some typical solids, volatile acid and pH profiles in the SOLCON digester are in Figure 3.

In addition, for water hyacinth/sludge blends periodic recirculation (3 to 4 h daily) of the upper portion of the digester culture volume is desirable and ensures degradation of the floating plant fraction. A special nozzle was effective in distributing the recirculated culture. The nozzle is available commercially and can readily be adapted to large-scale digesters.

Product gas treatment consists of a complete gas conditioning, storage, and handling system. A conventional house gas meter provided accurate readings during the two years of service. Calibration checks showed that the meter measured daily gas production with an accuracy of 1% to 2%. The reed switch counter on the gas meter was replaced with a microswitch to ensure reliable remote recording of the gas measurement. Gas quality is primarily determined by spot samples and gas chromatography. All pertinent data are continuously recorded on strip charts located on a main control panel.

Daily analyses of gas composition, effluent pH, volatile acids, total and volatile solids, and weekly analysis of total and volatile suspended solids and alkalinity are completed in a field laboratory trailer. Other analyses are conducted at IGT's laboratory in Chicago. Periodically, samples for daily and weekly analyses were sent to IGT to verify the results obtained at the ETU sentinels for the ETU digester. One 50 L unit is operated using the same blend as fed to the ETU digester, one 50 L unit receives pure water hyacinth and one 5 L unit is operated on pure sludge.

RESULTS

Experimental operation of the ETU began in January 1984. After a brief shake-down period, operation was begun with water hyacinth/sludge (WH/SL) blends in the upflow mode (Figure 4). Loading rates to the digester were controlled at 3.2 kg VS m^{-3} d^{-1} and an 11 d hydraulic retention time. Performance data were

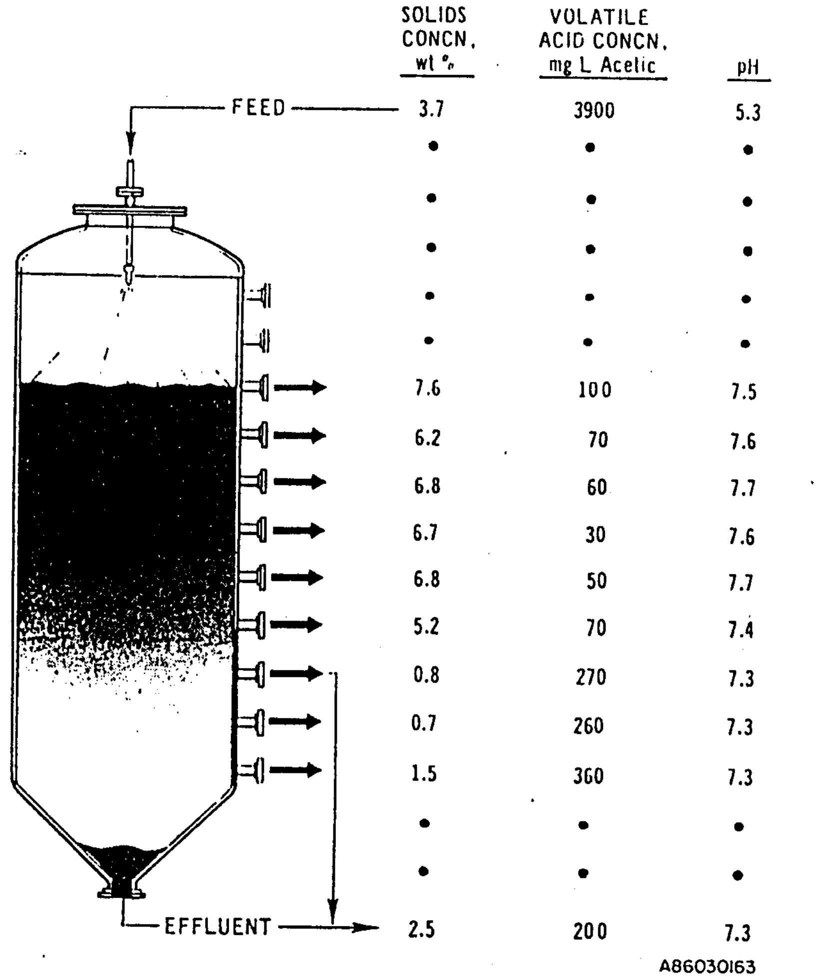

FIGURE 3. Digester profile for water hyacinth/sludge blend.

collected around the digester during two steady-state periods. One using a 2:1 WH/SL blend and one using a 1:1 WH/SL blend. Based on the solids distribution in the digester, operation was then switched to the downflow mode. Performance data were collected during four different steady-state periods. One studied long-term effects and one raised the loading rate to 4.9 kg VS m^{-3} d^{-1} and a seven day hydraulic retention time. The performance data for the six periods are summarized in Table 5.

Despite constantly changing operating conditions to establish a data base at different blend ratios and loading rates, the

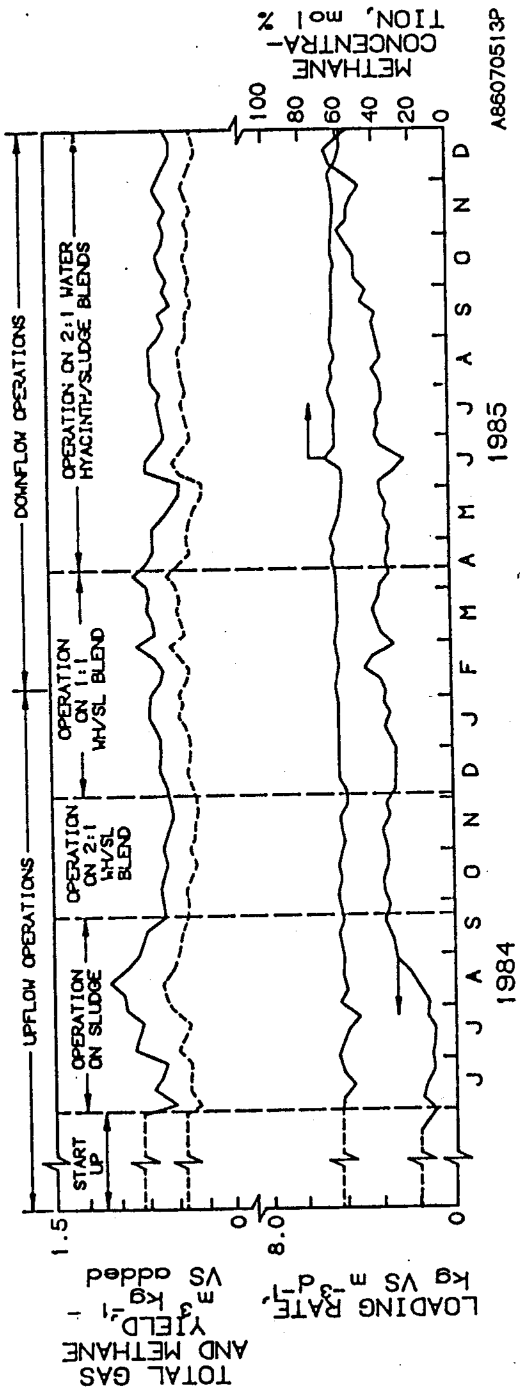

FIGURE 4. Biogasification ETU performance data water hyacinth/sludge blends.

digester operation was uninterrupted and always stable during 18 months of data collection. Hyacinth/sludge blends were converted to CH_4 at high rates and efficiencies. During operation on a 1:1 blend CH_4 yields averaged 0.49 m^3 kg^{-1} fed to the digester. This conversion exceeds 90% of the maximum biodegradable yield. Furthermore, in all cases the SOLCON digester outperformed the continuous stirred tank reactors operated at the site. As illustrated by Figure 5, the results obtained at a loading rate of 3.2 kg VS m^{-3} d^{-1} and different blend and flow configurations.

CONCLUSION

The improved performance in the SOLCON digester is primarily the result of higher solids retention (20 to 30 d) relative to the hydraulic retention time. In addition, net-energy recovery is also higher because continuous stirring of the reactor content is not required. Therefore, this digester produces 15% to 20% more CH_4 and results in smaller digester designs. During the two year operating campaign sufficient data were collected and a kinetic model (Srivastava, 1986) established to allow confident scale-up to larger commercial operations. In addition, independent studies by an engineering firm indicate that if the performance of the ETU

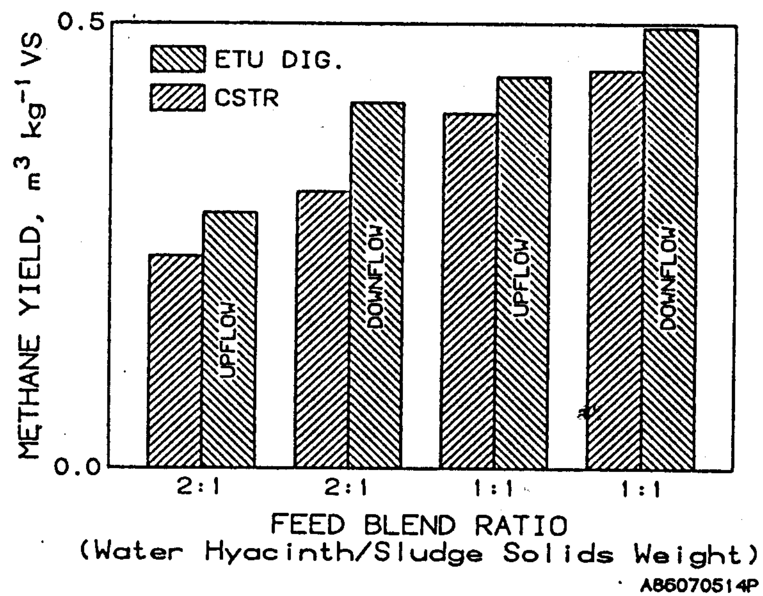

FIGURE 5. Performance comparison of CSTR and ETU digesters (3.2 kg VS m^{-3} d^{-1} loading rate).

TABLE 5. ETU steady-state performance data.

Performance Period	1	2	3	4	5	6
Date	11/5-12/2/84	1/21-2/10/85	3/25-4/21/85	8/5-9/1/85	9/2-9/29/85	12/16-1/12/86
Duration	4 wk	3 wk	4 wk	4 wk	4 wk	4 wk
Operating Mode	Upflow	Upflow	Downflow	Downflow	Downflow	Downflow
Digester Feed Characteristics						
Avg. Blend Ratio WH/PS, TS wt ratio	2:1	1:1	1:1	2:1	2:1	2:1
Avg. Solids Content, wt %	4.5	3.6	3.8	3.7	3.8	4.4
Avg. Volatile Solids Conc., wt % TS	84.6	87.1	85.5	85.6	86.5	83.2
Avg. Volatile Acids Content, mg L^{-1} acetic	3600	2600	3400	3900	2800	5000
pH	--	5.2	5.2	5.3	5.4	5.3
Avg. Alkalinity, mg L^{-1} $CaCO_3$	--	1900	3400	2900	3000	3860
Avg. NH_3-N Content mg L^{-1}	390	340	730	580	450	570
Digester Operating Conditions						
Daily Loading Frequency	1	1	1	1	1	1
Avg. Daily Loading Rate, kg VS m^{-3}	3.2	3.2	3.2	3.2	3.2	4.9
Culture Volume, m^3	3.8	3.8	3.8	3.8	3.8	3.8
Avg. Temperature, °C	35	35	35	35	35	35
HRT, d	12	11	11	11	10	7
SRT, d	21	17	30	24	25	13

TABLE 5 (cont'd.)

	1	2	3	4	5	6
Performance Data						
Total Gas Yield, m^3 kg^{-1} VS added	0.47	0.69	0.76	0.65	0.59	0.50
Methane Content, vol. %	60	63	64	63	63	59.1
Methane Yield, m^3 kg^{-1} VS added	0.28	0.43	0.49	0.41	0.37	0.30
Methane Yield, m^3 kg^{-1} organic matter added*	0.26	0.39	0.44	0.36	0.34	0.25
Percent of Maximum Biodegradable Yield**	63	84	92	86	83	62
Methane Production Rate, vol vol^{-1} culture d^{-1}	0.9	1.3	1.5	1.3	1.2	1.5
Carbon Conversion, wt %	40	59	62	55	51	42
Carbon Balance, wt %	98	105	103	108	99	94
Effluent Quality Data						
Avg. Solids Content, wt %	3.02	1.96	1.91	2.52	2.35	2.64
Avg. Volatile Solids Conc., wt % TS	74.5	78.0	75.1	74.6	77.3	73.0
Avg. Volatile Acids Content, mg L^{-1} acetic	2800	600	1100	200	100	2330
pH	7.3	7.2	7.2	7.3	7.3	7.1
Avg. Alkalinity, mg L^{-1} $CaCO_3$	6000	4700	5200	4800	4200	5240
Avg. NH_3-N Content, mg L^{-1}	870	850	1100	750	760	870

*Standard volatile solids (VS) determination does not account for volatile acids (VA).

**As measured by bioassays and based on a value of 0.3 m^3 kg^{-1} Org. for WE and 0.6 m^3 kg^{-1} Org. for WDW SL.

can be duplicated at the community scale, CH_4 can be produced from the SOLCON digester for less than \$2.00 GJ^{-1} for populations of over 100,000.

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